Economics of seasonal photovoltaic soiling and cleaning optimization scenarios

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Economics of seasonal photovoltaic soiling and cleaning optimization scenarios

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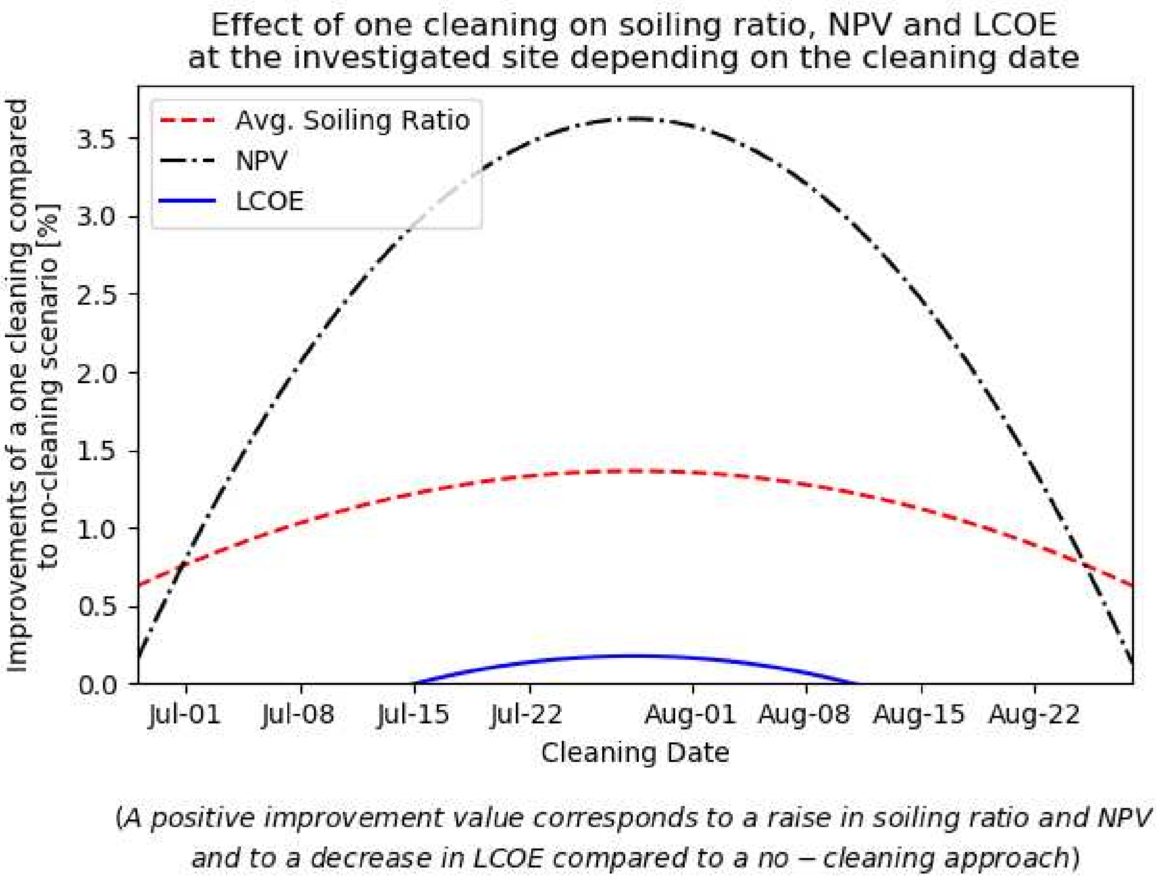
Abstract

The present study analyzes the soiling losses of a 1 MW system installed in the South of Spain. Both the Levelized Cost of Energy and the Net Present Value are used to compare the convenience of different mitigation strategies. It is found that also PV installations located in moderate regions, where the yearly soiling losses are limited to 3%, can suffer of a severe seasonal soiling, with power drops higher than 20%. In these conditions, an optimized cleaning schedule can be considerably beneficial from an economic perspective. For the given site, an optimal cleaning schedule generates a raise in profits up to 3.6% if one yearly cleaning is performed within a ± 31-day window in summer. The convenience of one and multiple cleaning strategies is investigated by considering variable electricity prices and cleaning costs. In addition, the impact of the module efficiency on the cleaning strategy is analyzed. It is found that an optimized cleaning schedule can enhance the benefits of installing high efficiency modules, as it increases the amount of energy recovered through each cleaning and, therefore, the profits.

Graphical Abstract



Nomenclature

A_{tech} [€/kW]	Surface of the module
C [€/kW]	PV system installation costs
CC_s [€/m^2/cleaning]	Surface Cleaning Cost
CC_{tech} [€/kW]	Technology-Specific Cost of Cleaning
C_W [€/kW]	Specific Cost of Cleaning for the whole PV site
C_{module} [€/kW]	Cost of the PV modules
C_{new} [€/kW]	Installation costs after module replacement
d [%/year]	Discount Rate
E_t [kWh/kW]	Yearly Energy Yield in conditions of no soiling
$E_{t,new}$ [kWh/kW]	Yearly Energy Yield with no soiling after module replacement
LCOE [€/kWh]	Levelized Cost of Electricity
NPV [€/kW]	Net Present Value
OM_t [€/KW/year]	Yearly O&M costs, cleaning excluded
P_{DC} [kW]	Installed capacity of a PV modules.
P_{tech} [kW]	Installed capacity of a type of PV modules.
p [€/kWh]	Electricity Price
R_D [%/year]	Linear degradation
r_s	Soiling ratio profile
T [years]	Years of operation
W_{tech} [€/kW]	Nominal power of the module
η_{new} [%]	Efficiency of the new modules chosen for replacement
η_{tech} [%]	Module Efficiency

Highlights

- Optimized cleaning schedules can be highly beneficial in seasonal soiling conditions
- The investigated site can be profitably cleaned within a 31-day window in summer
- For the given site and conditions, the NPV is more cleaning-prone than the LCOE
- The optimal cleaning number varies with the cleaning cost and the electricity price
- The profits of an optimized cleaning strategy increase with high-efficiency modules

Keywords

Photovoltaic, Soiling, Performance Ratio, Cleaning, Economics.

1. Introduction

Soiling consists of the accumulation of dust and pollutants on the surfaces of photovoltaic (PV) modules [1]. It causes a direct loss in the energy generation, because it scatters, reflects and absorbs part of the incoming sunlight, reducing the intensity of the energy that reaches the PV cell [2]. Soiling affects PV systems worldwide and has been estimated to have caused losses for more than 3 billion € globally in 2018 [3]. The impact of soiling can be mitigated through preemptive actions, which aim to prevent the deposition of dust on the modules or facilitate its natural removal [4], and/or through cleanings. A correct soiling mitigation strategy produces multiple benefits: it increases the revenues for the PV owners, it raises the capacity factor, it increases the PV market share without taking into account any newly installed capacity and, thanks to the higher profits, it could attract more investments in PV.

Currently, cleanings are the most common soiling mitigation strategy [3]. Indeed, preemptive technologies, such as anti-soiling coatings, can reduce the soiling deposition rate [5], [6], but cannot yet eliminate the need for cleaning [3]. Cleanings should be performed at times that maximize the electrical performance and, at the same time, minimize the electricity consumption and the costs. Indeed, cleaning a PV module that has limited soiling as well as not cleaning a soiled PV module cause avoidable losses of revenues [7]. In addition, it should be considered that rainfalls can also have a washing effect and can remove soiling from PV modules at no costs [8]. Cleanings operated just before of a rainfall can have, therefore, a low convenience, because they would increase the operating and maintenance (O&M) costs, with only a small or even no energy benefit. In some seasons and in some locations, rainfalls can keep the PV modules adequately cleaned, without the need of any artificial intervention [9]. For these reasons, various economic models have been proposed to identify the most convenient cleaning schedule.

A simple methodology for decision making on cleaning was proposed by Cristaldi et al. [10], and is based on performing the cleaning once the soiling revenue loss is higher than the cleaning costs. This is a method that can be easily applied to take O&M decisions on fielded PV systems, but leaves room for an additional optimization because it is based on matching the cleaning costs and the soiling revenue losses. In an optimal scenario, indeed, cleaning should be performed to minimize the soiling cost, intended as sum of revenue losses and mitigation costs [11]. Urrejola et al. [12] presented an economic analysis of soiling and cleanings for a PV system in Chile, considering also the effects of the electricity price and of the cost of cleaning. A method based on the maximization of the difference between revenues and cleaning costs was used by Besson et al. [13] also for PV systems in Chile. The same methodology was then used by Luque et al. [14] to evaluate the effects of soiling on bifacial modules. You et al. [15] identified the optimal cleaning schedules for PV systems in various cities worldwide by maximizing the Net Present Value (NPV). On the other hand, Rodrigo et al. [16] used the Levelized Cost Of Energy (LCOE) as metric to identify the optimal cleaning schedule for a PV installation in Mexico and investigated the influence of the parameters in input.

The present work analyzes the energy data of a real PV system installed in the south of Spain and investigates the economic impact of soiling and of various cleaning strategies. Differently from most of the previous works on the subject, the investigated site requires only a limited number of yearly cleanings, rather than periodic or frequent cleanings, as most of the soiling occurs in a specific season. The soiling and climatic conditions investigated in this work are common in various regions where a large PV capacity is installed, such as the Mediterranean area and the Southwest of the United States. Both the NPV and the LCOE are considered and compared in this work. For the first time, the different optimal strategies that the two metrics return are discussed in detail. The advantages and the disadvantages of multiple cleaning scenarios over a one or no cleaning approaches are investigated, even for variable electricity prices and costs of cleaning. Furthermore, the impact of the module efficiency on the calculation is thoroughly analyzed, and additional mitigation actions are proposed based on the findings.

The methodology proposed in this work could be applied to any PV system worldwide to support O&M teams in the identification of the most convenient cleaning schedules. The conclusions can also be of interests for PV system designers and investors to better estimate the economic costs of soiling and to plan the most convenient mitigation strategy accordingly.

2. Methodology

2.1. Energy yield and soiling losses

In this work, a PV site located in the province of Granada, in southern Spain, has been studied. The system has 10 inverters of 100 kW each and PV modules installed facing south at a tilt angle of 30°, for a total DC capacity of 961 kW. In 2019, an AC energy yield of 1718 kWh/kW was recorded, calculated as the total of the hourly AC power outputs of the inverters divided by the total AC capacity of the system.

Soiling has been quantified through the soiling ratio [17] and the soiling rate [18]. The daily soiling ratios are calculated as ratios between the actual DC power and the expected DC power, corrected according to the angle of incidence [19], the temperature and the spectral mismatch [20], using the *pvlib-python* library [21]. The POA irradiance was measured on site with a pyranometer, whereas temperature, pressure, and rain data were downloaded from MERRA-2 [22]. Minimum thresholds of 0.01 mm/hour and 1.0 mm/day were applied to the rainfall dataset. Hourly PV performance data were provided and only the central hours of the day were considered (11AM to 1PM) [17]. In addition, days in which the minimum irradiance for the central hours was lower than 700 W/m^2 were removed. No inverter clipping was detected.

The soiling profile, shown in the top plot of Fig. 1 (red line), was extracted from the DC power data of one string only using a methodology based on the modelling of each individual soiling period in between cleaning events (i.e. rainfalls or artificial cleanings) [23]. Linear soiling rates were considered and extracted using the Theil-Sen regression for any period longer than 14 days without cleaning events [18]. Only soiling rates with a fit of $R^2 > 0.1$ were considered valid. For periods shorter than 14 days or with no valid fit, a soiling rate of 0.0%/day was assumed. Missing daily soiling ratios were estimated through linear regression. The same soiling profile was applied to all the strings of the PV system.

Only two of the dry periods were found to have a valid soiling rate ($R^2 > 0.1$): the one in March and one between April and August. By looking at Fig. 1, it can be seen that a change in soiling rate occurred in mid-June 2019. This is due to an increased concentration of airborne dust registered from June 22th and associated to dust and sand-laden wind conditions. Two particulate monitors installed in the city of Granada showed a change in average daily PM_{10} concentration from 28.4 ± 5.5 μg/m^3 to 45.7 ± 6.5 μg/m^3 and from 25.8 ± 3.8 μg/m^3 to 38.0 ± 4.4 μg/m^3 for the 7 days immediately before and after June 22th [24]. Because of this change in conditions, instead of considering the slope of the whole summer dry period, this has been divided into two segments (see “Rate Change Date” in Fig. 1), here called “soiling rate periods”. In the first soiling rate period (lasting until June 22th), soiling deposits at a rate of -0.02%/day. In the second one, soiling deposits at a rate of -0.28%/day. Such a severe deposition rate is not uncommon for PV systems in Spain and in most of the top PV markets worldwide [3].

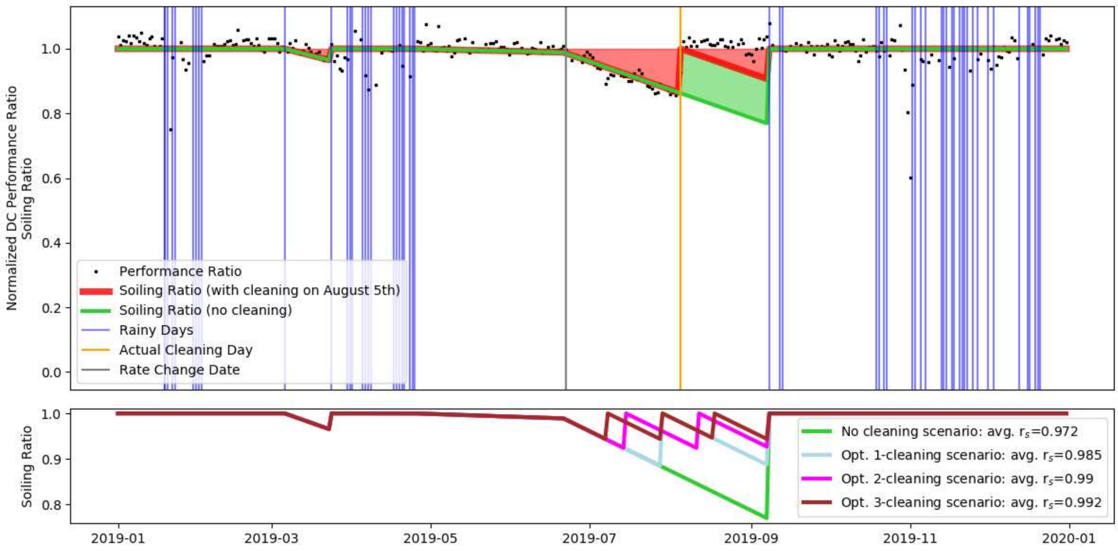


Fig. 1. Upper plot: normalized daily performance ratios (black dots), the actual soiling profile with the current model (red), and the soiling profile if no cleaning was performed on August 5th (green). The vertical lines mark: rainy days with intensities > 1 mm/day (blue), cleaning days (orange) and soiling rate change dates (grey). Lower plot: Soiling profiles for various cleaning optimization scenarios. Only scenarios with 3 or less cleanings are shown.

A cleaning was performed by the O&M team on August 5th, 2019. This will be referred to as the "*actual cleaning date*" in the rest of the paper. Some assumptions have to be made in order to predict how the soiling profile would have been without that cleaning: in this work it has been assumed that, in lack of a cleaning, soiling would have kept depositing on the modules at the same rate as previously until the first rain event (occurred in September 2019). In addition, no "grace period" has been modelled: soiling has been assumed to start depositing on the modules immediately after rainfalls or cleanings. According to the soiling profile generated using this methodology (green line in Fig. 1), the annual soiling loss without cleaning would have been 2.8%, with a daily maximum of 23.1% in summer. The 97% of the total yearly losses occurred in the long summer dry period, meaning that the site has an high seasonality [25].

The combination of high summer soiling rates and high rainfall seasonality makes this site particularly interesting for a study on the cleaning schedules. A limited number of summer cleanings, indeed, can produce potentially significant power and energy recoveries from soiling, and their optimization is the main subject of this work. Various potential cleaning scenarios are considered, with a number of yearly cleanings going from 1 to 6 (lower plot of Fig. 1). Differently from the previous literature on soiling cost mitigation, instead of considering the best cleaning interval, in this work the combinations of cleaning dates that maximize the yearly average soiling ratio are identified, independently of the time interval between them. The cleaning date algorithm is based on that proposed in [26], which was able to identify the best cleaning date to maximize the soiling ratio. In this work, the algorithm is improved to considered the possibility of more than one yearly cleaning dates. The seasonality of irradiance is neglected and will be added in future developments. Anyway, since all the best cleaning dates are in summer, the benefit of an irradiance-aware cleaning date optimization is expected to be limited for this site. The analysis presented in this work is based on the assumption of yearly linear degradation and of recurring rainfall and soiling deposition profiles.

2.2. Economic metrics and parameters

The Levelized Cost of Electricity (LCOE) quantifies the cost of producing a kWh of electricity. It is commonly employed to characterize utility-scale PV systems and to assess their cost competitiveness compared to other energy generation technologies [27], [28]. In this work, the LCOE is calculated by using the equation proposed by [27], without interest expenditures:

$$LCOE = \frac{C + \sum_{t=0}^{T} {(\mathrm{OM}_t + n_c \cdot C_W)}/{(1+d)^t}}{\sum_{t=0}^{T} r_s \cdot E_t \cdot {(1-R_D)^t}/{(1+d)^t}} \quad (1)$$

where T is total number of years of operation, C is the installation cost, OM_t is the yearly operation and maintenance cost (cleaning excluded), n_c is the number of yearly cleanings, C_w is the cost of each cleaning, d is the discount rate, r_s is the soiling ratio profile, E_t is the AC energy yield profile, and R_D is the degradation rate. The value of each parameter is shown in Table 1. It should be noted that all the costs are reported as euros per unit of power. E_t is the energy yield of the ten inverters inclusive of all the losses but soiling and has a value of 1752 kWh/kW. The product $r_s \cdot E_t$ corresponds to the sum of the products of daily soiling ratios and daily energy yield values. This approach makes it possible to give more weight to soiling occurring in summer, the season with the highest irradiance. When a scenario A and a scenario B are compared, the scenario A is considered convenient if the improvement, calculated as 1-$LCOE_A/LCOE_B$, is positive.

The Net Present Value (NPV) is commonly used in the private sector to evaluate the profitability of an investment [29]. It is defined as the difference between the present values of the cash inflows and cash outflows over the lifetime of the PV system and is expressed in monetary value [30]. The following equation, which makes use of the discount rate d, has been employed in this work [31]:

$$NPV = -C + \sum_{t=0}^{T} \frac{p \cdot r_s \cdot E_t \cdot (1-R_D)^t - (\mathrm{OM}_t + n_c \cdot C_W)}{(1+d)^t} \quad (2)$$

where p is the average price at which electricity is sold in the energy market (Table 1). A positive NPV means that the investment is profitable. When a scenario A and a scenario B are compared, the scenario A is considered profitable if the improvement, calculated as NPV_A/NPV_B-1, is positive.

Table 1. Value, units and source of the parameters used in this analysis. The asterisk marks that the value has been converted from US dollar, considering a 0.92 $/€ conversion factor.

Parameter	Symbol	Value	Units	References
Years of operation	T	25	years	
Energy yield in conditions of no soiling	E_t	1752	kWh/kW	
O&M costs, cleaning excluded	OMt	15	€/KW/year	[32] *
Installation Costs	C	700	€/kW	[33]
Surface Cleaning Cost	CC_s	0.09	€/m^2/cleaning	[3]

Electricity Price	p	0.06	€/kWh	[3]
Discount Rate	d	6.4	%/year	[32]
Linear degradation	R_D	1.0	%/year	

The site considered in this work is made of modules from various manufacturers and with different efficiencies (Table 2). The Surface Cleaning Cost (CC_s) can be converted into a Technology-Specific Cost of Cleaning (CC_{tech}, in €/kW) for each module type (*tech*) by considering the area (A_{tech}) and the nominal power (W_{tech}) of the module or its efficiency (η_{tech}):

$$CC_{tech}[\frac{€}{kW}] = \frac{CC_s \cdot A_{tech}}{W_{tech}} \cdot 1000\ W/kW = \frac{CC_s}{\eta_{tech} \cdot 1000\ W/m^2} \cdot 1000\ W/kW \tag{3}$$

No fixed costs are considered when a cleaning is performed. The Specific Cost of Cleaning for the whole site only depends on each PV module type's cleaning cost and capacity (P_{tech}):

$$C_W[\frac{€}{kW}] = \sum_{tech=A}^{G} \frac{CC_{tech} \cdot P_{tech}}{P_{DC}} \tag{4}$$

being P_{DC} the PV site DC capacity (961 kW). At the considered conditions, the specific cost of cleaning for the present site is 0.62 €/kW.

Table 2. Capacity, Efficiency and Specific Cleaning Cost of each module type installed at the site. The technology specific cleaning cost has been calculated by considering a Surface Cleaning Cost of 0.09 €/m²/cleaning.

Module Type	**Installed Capacity [kW]**	**Module Efficiency [%]**	**Technology Specific Cleaning Cost [€/kW/cleaning]**	**Percentage of the PV site DC capacity [%]**	**Percentage of the PV site Specific Cleaning Cost [%]**
Module A	10	12.9%	0.70	1.0%	1.2%
Module B	26	14.5%	0.62	2.7%	2.7%
Module C	92	14.3%	0.63	9.6%	9.7%
Module D	176	13.3%	0.68	18.3%	20.0%
Module E	194	14.1%	0.64	20.2%	20.7%
Module F	205	13.7%	0.66	21.3%	22.6%
Module G	258	16.7%	0.54	26.8%	23.2%

3. Actual and Optimized Cleaning Schedule

In this section, the impact of the cleaning performed on August 5th by the O&M team is evaluated from both an energy and an economic perspective. Its convenience is compared to that of a cleaning performed on the optimal cleaning day. In addition, the effects of multiple cleaning scenarios on the LCOE and the NPV are investigated.

From an analysis of the soiling profiles, it can be seen that the cleaning performed in August, made it possible to recover 53.9% of the energy otherwise lost for soiling, raising the average soiling ratio to 0.985. The economic impact of that cleaning can be quantified by analyzing the variation in LCOE and NPV for the two scenarios (Table 3). The actual cleaning led to an increase in soiling ratio (i.e. reduction in losses) and to a larger raise in energy yield. This is due to the fact that most of the soiling occurred in summer, when the irradiance is higher. Therefore, for this site, if it is not mitigated, soiling causes losses to the energy yield higher in percentage than those estimated with the simple average soiling ratio. For this reason, in conditions of seasonal soiling, it is important to consider in equations (1) and (2) the daily profiles of soiling and energy yield, rather than their average values. The cleaning had a positive effect on both the LCOE and the NPV, meaning that it lowered the cost of the energy produced by the PV system and it also increased the profits.

Table 3. Improvement in soiling ratio, energy yield, LCOE and NPV compared to a no-cleaning scenario if a cleaning is performed on the actual cleaning date or on the optimal cleaning date. A positive improvement corresponds a raise in soiling ratio, energy yield and NPV and to a decrease in LCOE.

	Soiling ratio	Energy Yield	LCOE	NPV
Actual cleaning	1.32%	1.57%	0.13%	3.43%
Optimal cleaning	1.36%	1.63%	0.18%	3.63%

If the actual cleaning date is compared with the optimal cleaning date, determined by using the model described in Section 2.1, it is found that the actual cleaning was performed with a 7-day delay compared to the optimal case. An optimal cleaning would have led to an additional absolute increase of 0.04% in soiling ratio and of 0.20% in NPV compared to the actual cleaning. Also, the improvement in LCOE would have been about 50% higher.

It is possible to investigate the effect of a premature or of a delayed cleaning by studying the soiling accumulation trend. In particular, it is of interest to look at the curve showing how the average soiling ratio changes depending on the cleaning day (black line in the left plot in Fig. 2). Each non-flat portion of this curve corresponds to a different soiling rate period and follows a parabolic trend (because of the linear soiling rate assumption). The peak of the curve is reached on the cleaning optimization date, and corresponds to the maximum achievable value of yearly soiling ratio for a cleaning performed in that period. The LCOE and the NPV follow similar parabolic trends in each soiling rate period, with different fitting parameters. The analysis of the parabolic trends during the most intense soiling period, shown in the right plot of Fig. 2, confirms the results of Table 3: the actual cleaning date intercepts the parabolas near to their vertexes, therefore returning just slightly lower improvements in soiling ratio, LCOE and NPV than the optimal case. In addition, it is interesting to note that the NPV curve shows that any cleaning performed within ± 31 days of the optimal cleaning date would have had a positive effect on the NPV. On the other hand, this window was limited to ± 13 days for the LCOE.

It is not surprising to see the LCOE and the NPV returning different trends for the same site and the same periods. This is due to the different structure of the two indexes. Indeed, as discussed in Ref. [16], the installation and O&M costs have a significant effect in determining the most advantageous cleaning schedule when the LCOE is considered. On the other hand, for the NPV, the cleaning become convenient when the following criterion is met:

$$CC_W \leq p \cdot (r_{s1} - r_{s0}) \cdot E_t \cdot \sum_{t=1}^{T} (1 - R_D)^t \tag{5}$$

being r_{s1} and r_{s0} the soiling ratio values in a one cleaning scenario and in a no-cleaning scenario, respectively. As shown in the equation, the NPV cleaning decision is based on the cleaning cost, the electricity price, the energy yield, the degradation rate and on the amount of losses recovered thanks to the cleaning. The installation and the fixed O&M costs do not impact the decision on the most profitable cleaning schedule, but they still affect the value of the profits. This means that the variation of the installation and O&M costs will vary the vertex of the NPV parabolic trend, but will not affect the x-intercept points (i.e. the positive NPV improvement window).

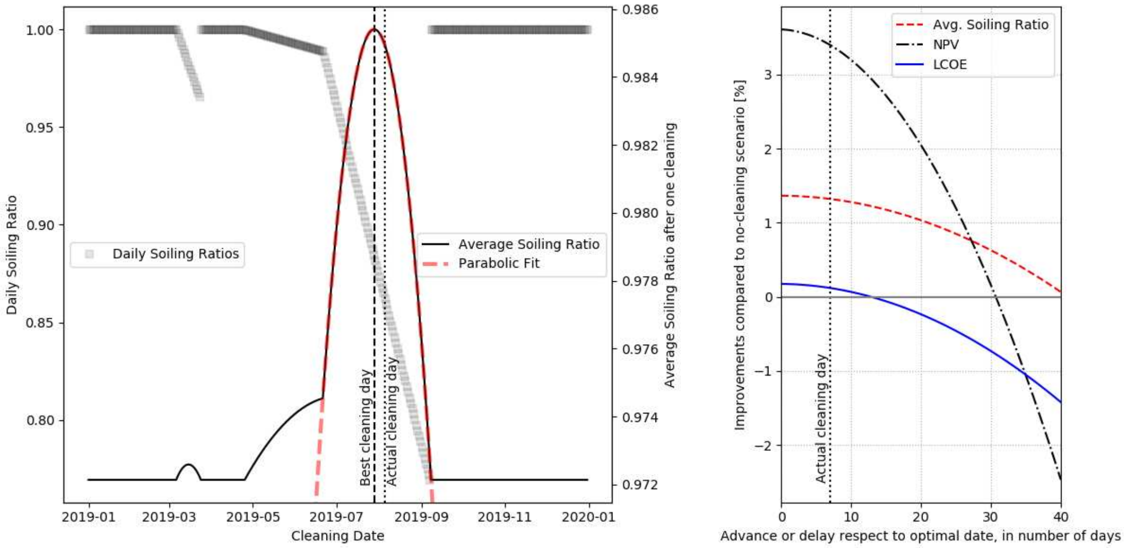


Fig. 2. Left plot: Daily soiling ratio values (grey markers, left y-axis). Variation of the average soiling ratio depending on the day a cleaning is performed in a one-cleaning scenario (black continuous line, right y-axis). The red dashed line shows the best parabolic fit for the average soiling ratio line during the longest dry period (right y-axis). Right plot: Improvements in soiling ratio, LCOE and NPV depending on the number of days of difference between the optimal cleaning day and the day in which the cleaning is performed. A positive improvement value corresponds a raise in soiling ratio and NPV and to a decrease in LCOE. Each parabola is symmetric with respect to the y-axis: advances or deferrals of fixed numbers of days compared to the optimal cleaning day produce the same improvements.

The possibility of performing multiple yearly cleanings has been also investigated. The results show that an optimized one cleaning scenario is more profitable than any multiple cleaning approach (Fig. 3). While the two economic indexes agree on this finding, they are in disagreement regarding the convenience of multiple cleanings over a no-cleaning scenario. According to the LCOE, it would be better not to clean rather than cleaning more than once a year. On the other hand, up to three yearly cleanings would be more profitable than a no cleaning scenario.

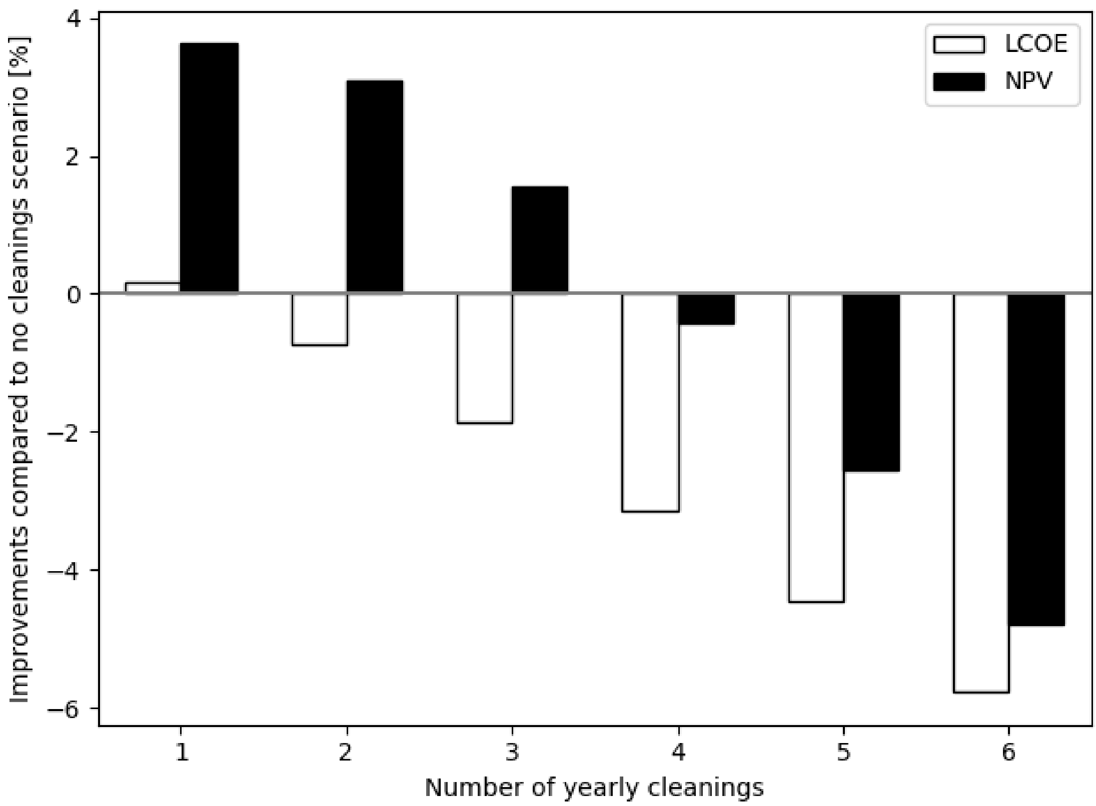


Fig. 3. Improvement, in %, between various cleaning scenarios compared to the no-cleaning scenario. A positive improvement value corresponds to a decrease in LCOE and/or a raise in NPV.

4. Mitigating Factors

In the previous section the convenience of various cleaning schedules was analyzed by taking into account the current cleaning costs and electricity prices. The surface cost of cleaning takes into account the price of the material and of the workforce [10], [11] and it varies depending of the country, but it can also vary within the same country [3]. The variations are due to different factors, such as the type of cleaning, the water availability, the site accessibility, the system configuration and/or the labor costs. Also the average electricity price varies yearly from country to country [34]. For this reason, the previous analysis has been repeated by taking into account variable cleaning costs and electricity prices.

Fig. 4 shows how the optimal number of cleanings would change, for the given site, for different surface cost of cleanings. As expected, the number of cleanings tends to increase while the surface cost of cleaning lowers. The NPV is still found to be the most "cleaning-prone" parameter, with higher numbers returned compared to the LCOE for surface costs of cleaning ≤ 0.07 €/m^2. The LCOE does not recommend any yearly cleaning for CC_s ≥ 0.11 €/m^2, a scenario that is recommended by the NPV only for CC_s > 0.25 €/m^2.

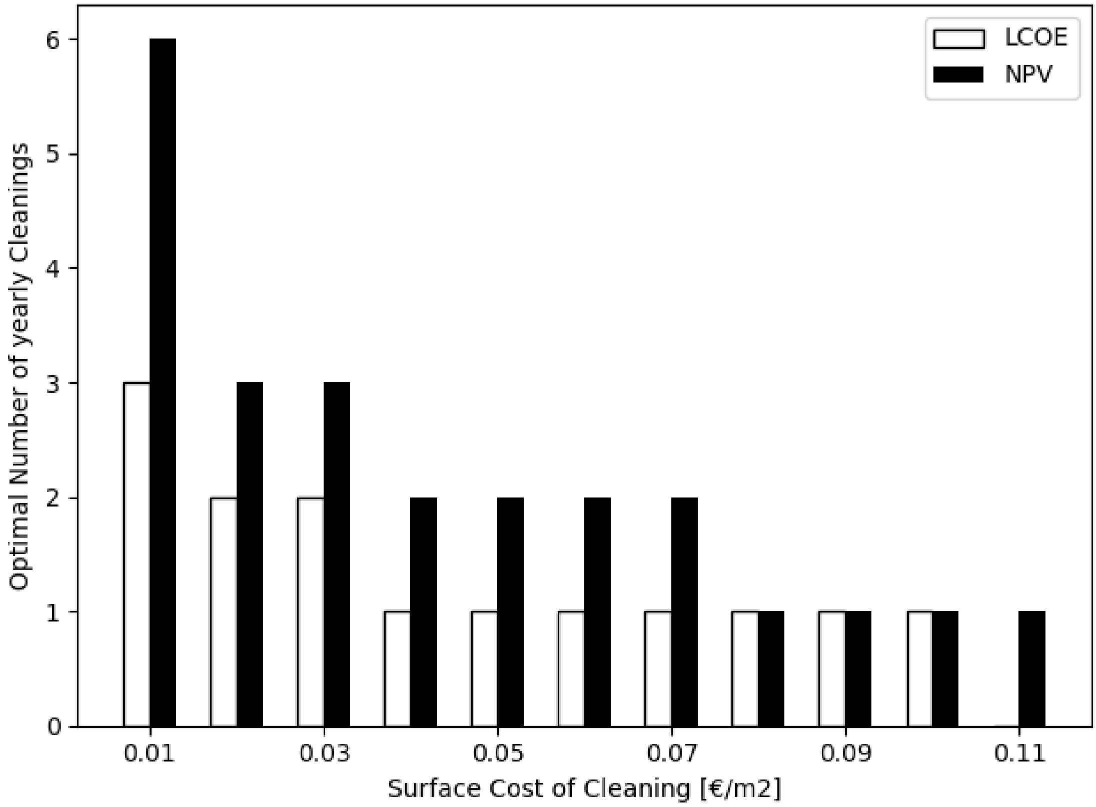


Fig. 4. Optimal number of yearly cleanings depending on the surface cost of cleaning.

Higher electricity prices can incentivize soiling mitigation and, in particular, cleaning operations, because, given the same cost, each kWh of recovered energy would return higher profits. Fig. 5 shows the optimized number of cleanings when both the electricity prices and the surface cost of cleanings are varied. As expected, the most favorable conditions to perform more cleanings are high electricity prices and low cleaning costs. These are also the conditions that would minimize the soiling losses and maximize the energy yield.

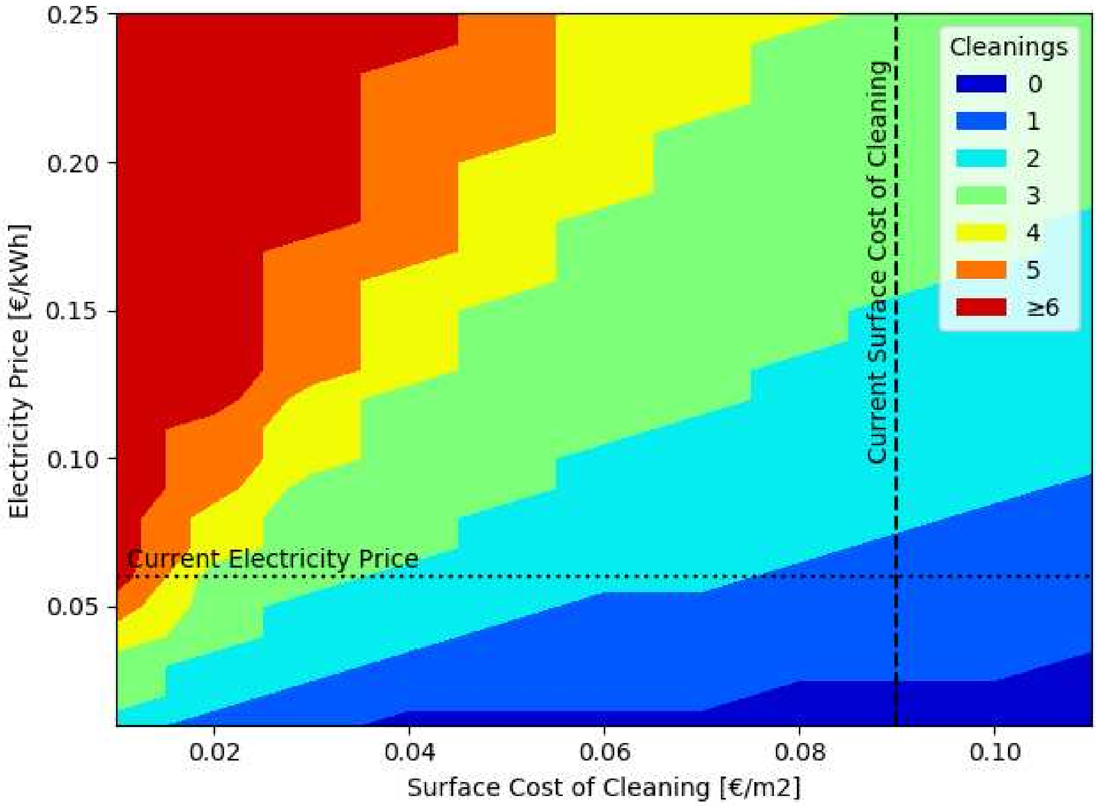


Fig. 5. Optimal number of cleanings to maximize the NPV depending on both variable electricity price and surface cost of cleanings. The vertical dashed line and the horizontal dotted line mark respectively the surface cost of cleaning and the electricity price considered in this study.

In addition to the surface cost of cleaning, the whole PV site's Specific Cost of Cleaning is affected by a second parameter, i.e. the module efficiency. The site under investigation is made of seven types of PV modules, with efficiencies ranging from 12.9% to 16.7%. Higher module efficiencies would cover a reduced surface to reach the same installed PV capacity. This means that, given a constant surface cost of cleaning, higher module efficiencies would lower the expense for cleaning the full PV site, and therefore change the optimal cleaning schedule. For this reason, the analysis has been also repeated to consider the whole site made of PV modules of the same efficiency, varying from 12.9% to 22.0%.

Assuming a different module efficiency has two effects on the calculations. First, it varies the Specific Cost of Cleaning, because, as mentioned, higher efficiencies reduce the surface to be cleaned, and vice versa, if the capacity of the site is kept constant. Second, different PV module efficiencies change the energy yield. Here, the variation is considered to be proportional to the difference in efficiency between new and currently-installed modules (η_{new} and η_{tech} respectively):

$$E_{t,new} = E_t + \sum_{tech=A}^{G} (\eta_{new} - \eta_{tech}) \cdot \frac{P_{tech}}{P_{DC}} \qquad (6)$$

No change is found for the LCOE optimal number of cleanings when the efficiency of the modules is varied: the one-cleaning scenario is always found to be the best. On the other hand, a two-cleaning approach becomes more profitable for PV modules of efficiency ≥ 17.8%. None of the

PV modules installed at the site has that efficiency, otherwise differentiate cleaning schedules could have been recommended for PV modules of efficiencies higher than that threshold.

It is interesting to note that, assuming an optimal cleaning schedule, an additional increase of 0.09% in profits per unit of module efficiency is found compared to a no soiling mitigation strategy (R^2=0.99 in the efficiency range 12.9% to 22.0%). This means that an optimized cleaning schedule rises the benefits of installing high-efficiency modules, and this is expected to become more significant as soiling becomes more severe. Therefore, one could replace the PV modules of a site with modules of higher efficiencies and have part of the replacement costs covered by the enhanced profits of an optimal soiling mitigation.

It should be noted, though, that PV modules still represent 30% to 50% of the PV installation cost, with prices in Spain ranging between 230 and 340 €/kW [33]. In order to account for all the effects of a PV module replacement, the previous analysis has been repeated by taking into account that changing the PV modules would also lead to a raise in installation costs equal to:

$$C_{new} = C + \sum_{tech} C_{module} \cdot \frac{P_{tech}}{P_{DC}} \tag{7}$$

where C_{module} is the module cost. The analysis was therefore repeated by taking into account these additional installation costs. Few assumptions were made. The cost for replacing low-efficiency modules was considered equal to the PV module cost and no additional expense was taken into account. In addition, different degradation rates and degradation conditions between the new and the replaced modules were neglected. Also, the same financial conditions as before were maintained.

The convenience of a module replacement depends on a number of factors: the PV module cost and efficiency, the electricity price and the cost of cleanings. The results of this analysis are shown in Fig. 6, where the combinations of conditions in which a module replacement would be profitable are reported. The light grey hatched area shows the conditions for which the module replacement would be convenient if no soiling mitigation was operated. The darker grey dotted area takes instead into account the optimal cleaning schedule. The current PV module cost (as low as 230 €/kW in Spain) and electricity price (0.06€/kWh) are not enough to economically justify, at the given site, the replacement of the PV modules, even considering the highest efficiency modules. Anyway, an optimized cleaning schedule makes the PV module replacement convenient in a wider range of conditions, compared to a case with to soiling mitigation in place. Even in the darker hatched area of the plots, where the module replacement is convenient for both no mitigation and the optimal cleaning approaches, this last is found to be more profitable. For these reasons, despite the impossibility of justifying the module replacement only because of the optimized soiling mitigation profits at the given site, this scenario should be further investigated, as it might become profitable in conditions of higher soiling losses or of different economic variables.

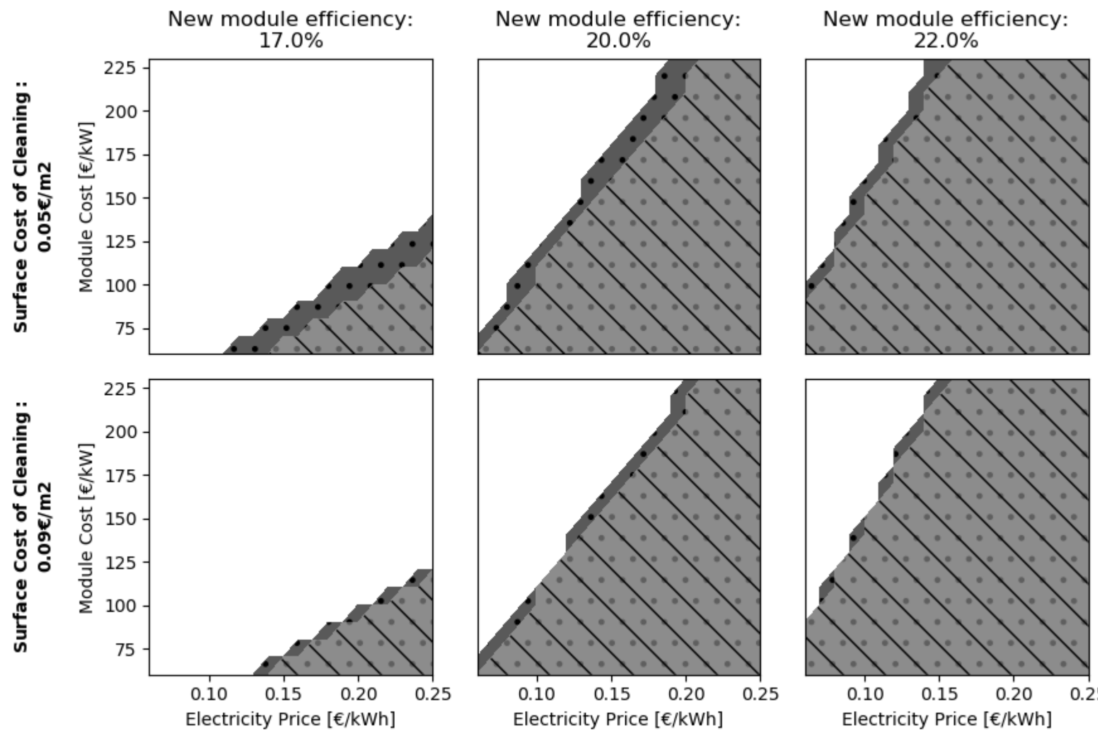


Fig. 6. Combinations of conditions to get a positive NPV improvement thanks to module replacement. The light gray and hatched area marks the conditions for which a module replacement increases the NPV if no soiling mitigation is in place. The darker dotted area shows the conditions for which a module replacement increases the NPV given an optimized cleaning approach.

5. Conclusions

In the present work, the analysis of the soiling losses occurred at a 1MW PV site in Southern Spain is presented and the potential mitigation strategies are discussed in details. It is found that, despite a limited 2.8% yearly soiling loss, an optimized cleaning schedule can provide a significant economic benefit, with an increase in profits up to 3.6%. This is due to the high seasonality of the site, where power drops higher than 20% can be experienced if no mitigation is performed due to the high soiling deposition rates occurring during the long dry summer.

The most convenient cleaning schedules are identified through the analysis of the NPV and of the LCOE, by taking into account a typical cleaning cost for the region. The two indexes are found to be differently affected by the soiling mitigation strategies, mainly because of the weight that the installation and the O&M costs have on the LCOE, and that the electricity price has on the NPV.

For the investigated site, a single cleaning scenario is found to be the most profitable, and also the one returning the lowest LCOE. From the calculation, it is found that, even if profitable, the cleaning operated on the site in summer 2019 had a 7 days' delay compared to the date that would have maximized the NPV. This decreased the profit raise by 0.2%. Overall, for this PV site, there is a ± 31-day window in which the cleaning could be operated with a positive effect on the NPV compared to a no-cleaning scenario. This window is smaller if an improvement in LCOE is aimed. It is also found that any number of cleanings up to 3, performed on optimal cleaning dates, would return better profits than no cleaning. As discussed in the sensitivity analysis here presented, the number of optimal cleaning increases as the surface cost of cleaning decreases and as the electricity price increases.

For the first time, the module efficiency has been investigated as factor affecting the cost and the effectiveness of each cleaning. It is found that the profitability of an optimized cleaning schedule increases with the PV module efficiency. In addition, it is found that, even in conditions of low yearly soiling, replacing the PV modules with higher efficiency ones could become profitable in an optimal soiling mitigation scenarios, thanks to reduced cleaning costs and the higher energy recoveries. The conditions under which the PV module replacement could become profitable at the given site are discussed in detail. Further investigations in this direction should be conducted in locations with higher soiling losses and in conditions of different module and electricity prices.

The findings of this work could find use in locations that share similar soiling and climatic conditions to those of the investigated site, common in regions such as Southern Europe or the Southwest of the United States. The methodology presented in this work can be used to assess the soiling loss and the mitigation strategies of any PV system, and to identify the most convenient cleaning schedules. In future, the methodologies should be improved, by taking into account the inter-annual variations of rainfalls and soiling deposition, and the potential non-linearity of degradation rates. In addition, further analysis should be conducted in future to understand how and if the deposition rates are affected by artificial cleanings.

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CRediT authorship contribution statement

Leonardo Micheli: Conceptualization, Methodology, Data Curation, Formal analysis, Investigation, Software, Visualization, Writing - original draft, Writing - review & editing, Funding acquisition, Project administration. **Eduardo F. Fernandez**: Data Curation, Validation, Writing - review & editing, Supervision, Funding acquisition. **Jorge T. Aguilera**: Data Curation, Writing - review & editing. **Florencia Almonacid**: Writing - review & editing, Supervision, Funding acquisition.

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